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ELECRONICS ORIGINAL ARTICLE

Resource Allocation Based on Channel State Information in OFDM Systems

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ABSTRACT

Orthogonal Frequency-Division Multiplexing is a modulation scheme specifically designed to facilitate high-speed data transmission over frequency-selective fading channels. Resource allocation based on channel state information is known to be a very powerful method for improving the spectral efficiency of Orthogonal frequency-division multiplexing systems. In case of static channels, the optimal resource allocation for multiuser Orthogonal frequency-division multiplexing systems has been investigated. For time-varying channel, the error in channel state information due to channel variation is recognized as the main obstacle for achieving the full potential of resource allocation. Finally, a maximum likelihood receiver for Multiband Keying signals is studied, where multiband keying is a modulation scheme proposed for ultra wideband systems. The receiver structure and the associated maximum likelihood decision rule is derived through analysis. A suboptimal algorithm based on a depth-first tree search is introduced to significantly reduce the computational complexity of the receiver.

Keywords: Orthogonal frequency division multiplexing, multiband keying, Resource allocation

I. INTRODUCTION

Wireless communications industry has been expanding dramatically in part due to great progress in the areas of digital signal processing, In recent years, in order to satisfy the increasing demand for higher data rates, much attention has been devoted to broadband wireless communication systems. Orthogonal frequency-division multiplexing (OFDM) system has a property of transforming a broadband channel into multiple narrowband sub channels.

Additional advantages of the OFDM system include high spectral efficiency, simple transceiver design, flexibility in terms of link adaptation, and so on. In the OFDM system, the effect of channel on each OFDM symbol is characterized by a complex vector known as the channel frequency response (CFR) [1]. The received complex symbols in all sub channels experience attenuation and phase shift determined by the CFR. Hence, for the purpose of coherent demodulation, CFR need to estimate at the receiver. For this reason, channel estimation has received a great deal of attention in OFDM systems.

A major drawback of the OFDM system over frequency-selective fading channels is the high probability of bit error rate (BER) due to the possible existence of “weak” subcarriers.

For the sake of reliable communication, an approach using forward error-control code and frequency and/or time interleaving may be employed, which results in the so-called “Coded-OFDM (C-OFDM)” system [2]. Among them is the emerging Ultra Wideband (UWB) technique, which is based on a principle totally different from that of the OFDM system. It suggests using extremely narrow pulse signals that have a period of up to several nanoseconds to modulate data symbols. UWB comes from the fact that an extremely narrow pulse in the time domain corresponds to an ultra wide bandwidth in the frequency domain.

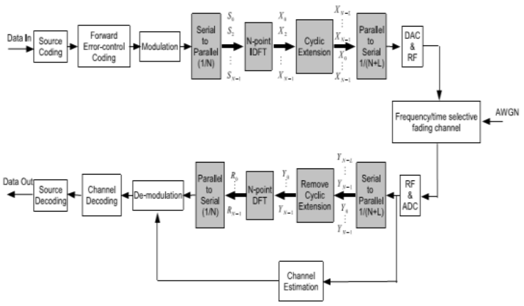

Fig. 1. The architecture of a typical OFDM system

Meanwhile, the transmit power has been dispersed into multiple (independent) components, and a RAKE receiver is needed to collect these components for better decision [3]. UWB system known as "Multiband Keying" is addressed, whose maximum likelihood (ML) receiver over AWGN channel is investigated.

II. OFDM SYSTEM OVER FREQUENCY-SELECTIVE FADING CHANNELS

As mentioned in [1], OFDM systems can be realized with low complexity using the discrete Fourier transform (DFT). The structure of a typical OFDM system is illustrated in Figure 1.1, where the shadowed blocks correspond to the processing of OFDM. In this system, the number of subcarriers is denoted by N and the sampling rate is fixed to be 1/TS, where TS = 1/(NΔf) and where Δf is the frequency offset between neighboring subcarriers.
Let {S0,k, · · · , SN−1,k} denote the complex symbols that are transmitted within the k^{th} OFDM block. Then the output of the IDFT module in Fig. 1 can be represented by

$$X_{m,k} = \sum_{n=0}^{N-1} S_{n,k} \cdot e^{j2\pi \frac{mn}{N}}, \quad m = 0, 1, \cdots, N-1 \tag{1}$$

Let c(τ; t) denote the equivalent lowpass impulse response of a time-varying, frequency-selective multipath fading channel. According to [4], c(τ; t) can be written as follows

$$c(\tau; t) = \sum_{i=0}^{I-1} \alpha_i e^{-j2\pi\{(f_c+f_{d,i})\tau_i - f_{d,i}t\}} \delta(\tau - \tau_i) \tag{2}$$

where I denotes the number of propagation paths, and τi, αi, and fd,i are, respectively, the propagation delay, the attenuation factor and the Doppler frequency offset for the i^{th} path. Moreover, δ(·) is the Dirac delta function, and fc is the center carrier frequency. The received baseband signal is given by

$$\begin{aligned} y(t) &= \int_0^\infty c(\tau; t) x(t-\tau) d\tau + \zeta(t) \\ &= \sum_{i=0}^{I-1} r_i(t) x(t-\tau_i) + \zeta(t) \end{aligned} \tag{3}$$

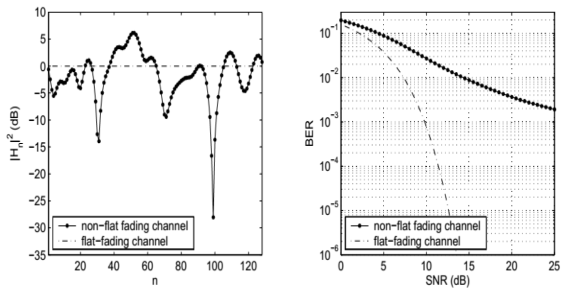

Fig. 2. Performance of OFDM systems with uniform bit and power allocation

The main drawback of this approach is its poor performance in terms of bit error probability under frequency-selective ("nonflat") fading channels. Figure 2 highlights this problem by comparing the system's bit error rate (BER) over a given non-flat fading channel with that of a flat fading channel. In this figure, QPSK modulation has been used for all subcarriers. Fig 2 illustrates an example of bit and power allocation scheme designed for the non-flat fading channel profile shown in Figure 2. In this case, the number of bits sent by each OFDM block is the same as that of Figure 2. The performance of this bit and power allocation scheme is compared with the that of the flat fading channel with uniform bit and power allocation, and the results are plotted in Figure 3. It can be seen by comparing performance curves in Figure 2 and Figure 3 that the OFDM system using resource allocation has a much higher spectral efficiency than the system without it.

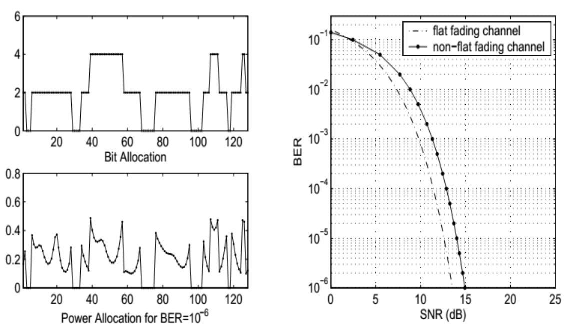

Fig. 3. Example of bit and power allocation for a non-flat fading channel

III. COMPUTATIONALLY EFFICIENT RESOURCE ALLOCATION FOR MULTI-USER OFDM SYSTEMS

The optimal subcarrier, bit and power allocation is a challenging task and its complexity is prohibitive in practical communication systems [5, 7]. To avoid this difficulty a tractable approach is to divide this problem into two separate problems: first find the optimal allocation for subcarriers to users, next, given the assignment of subcarriers, find the optimal allocation of bit and transmit power for each user. While the first step exploits the multiuser diversity, the second step makes use of the frequency diversity for each user. The main difficulty with the algorithms proposed in these references is their high computational complexity. While these algorithms may be applicable in wire line applications where the CSI remains static for extended periods of time, they are not suitable for the wireless environment where, even in the case of slowly fading channels, the CSI needs to be updated (and the solution recalculated) after several OFDM blocks. a novel method for subcarrier, bit and power allocation. We also consider the problem in two steps: subcarrier allocation to all the users followed by bit and power allocation for each user. Our algorithm achieves a near optimal solution with considerably less computational complexity than the optimal solution.

IV. AN EFFICIENT ALGORITHM FOR BIT AND POWER ALLOCATION.

In this section we temporarily ignore the problem of subcarrier allocation and assume that all the subcarriers have been pre-allocated to users. As a result the total number of subcarriers and the associated channel frequency response will be fixed for every user. The optimal bit and power allocation can now be solved for a single user. Thus in the rest of this section we drop the subscript k and use N to denote the total number of subcarriers assigned to the individual user of interest.

$$\min_{\{\beta_n\}} \sum_{n=1}^{N} \frac{\sigma_V^2}{|H_n|^2} \cdot f(\beta_n, \varepsilon) \quad (4)$$

Subjected to

$$\sum_{n=1}^{N} \beta_n \geq R$$
$$\beta_n \in \Omega,\ \forall n = 1, 2, \cdots, N. \quad (5)$$

The above is a mixed integer programming (MIP) problem requiring an exhaustive search with high computational complexity. In [8] the authors proposed a greedy method to assign bits iteratively until the target data rate is reached. During each iteration one more bit is added by searching for the smallest additional power necessary to guarantee the target BER.

V. AN EFFICIENT SUBCARRIER ALLOCATION METHOD

As mentioned previously the optimal allocation of subcarriers requires the solution of the constrained optimization problem which is computationally prohibitive. To get around the complexity issue, the problem of subcarrier allocation may be studied without involving bit and/or power allocation. In [9] it is shown that if the constraint in above is removed, then the optimal subcarrier allocation is to assign each subcarrier to the user whose power gain is the largest in that subcarrier. This approach, however, is unfair as it penalizes users whose channel power gains are small.

$$\sum_{n=1}^{N} \rho_{n,k} \geq \left\lceil \frac{R_k}{b_L} \right\rceil \ \forall k = 1, 2, \cdots, K \quad (6)$$

It is clear that any subcarrier allocation method that satisfies must also satisfy In other words is a necessary condition so that the data rate requirement of all users is satisfied.

VI. PERFORMANCE OF THE ABPA ALGORITHM

1,000 independent realizations of CFR using a 9-path outdoor channel model were generated [4]. The power delay profile for the simulated channel model is exponentially decaying with the maximum excessive delay of 5µs [4]. Specifically, the delay of these 9 rays are randomly generated within the 5µs interval while their amplitudes undergo independent Rayleigh fading. The CFR is generated by taking N-point discrete Fourier transform (DFT) for the samples of channel impulse response, where the sampling rate is NΔF = 2.56MHz. The resulting total

receive power for all the subcarriers is calculated from the algorithm for each CFR realization and then averaged over the 1,000 realizations to obtain Pave(ε, R). The average SNR is then calculated as

$$\overline{\nu} = 10\log_{10}\frac{P_{\text{ave}}(\varepsilon, R)}{N\sigma_V^2} \quad (\text{dB}). \tag{7}$$

Two values of R = 256 and R = 512 were used. Figure 4 illustrates the simulation results where BER ε is plotted vs. the SNR ν. In this figure the performance of the proposed ABPA algorithm is compared with that of the greedy method in [8] which is labelled as "optimal". For comparison the results for the non-adaptive OFDM system, where bit and power allocation is identical for all subcarriers has also been plotted. From Figure 4 we can see that the performance of the proposed ABPA algorithm is almost the same as the optimal method of [8] and is at least 10dB better than the non-adaptive system for BER 10−3. The complexity of our algorithm is, however; significantly lower than that of the optimal solution. The number of iterations required for the ABPA algorithm to terminate is less than 7 in most cases. The worst case we observed involved only 14 iterations.

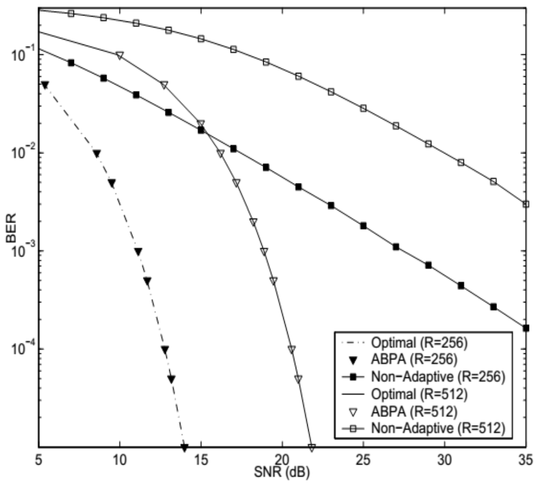

Fig. 4. Performance of the ABPA algorithms

VII. PERFORMANCE OF THE SA ALGORITHM

We now consider a MU-OFDM system with K = 5 users. The CFR for these users are randomly selected from the aforementioned channel realizations. The target BER for all users are set to the same value ε. For various users the target data rates and the average channel power gain given by Pn |Hn,k| 2 can be different. We have simulated two cases whose configurations are given in Table 3.1. In both cases we compare three different subcarrier allocation schemes. One is the algorithm presented in [10] and it is denoted by "WSA". Another is our proposed subcarrier allocation algorithm which is referred to as "SA". The third is a rate proportional FDMA scheme which yields a fixed subcarrier allocation, and is denoted by "FSA" [6] Fig. 5 and 6 illustrate the simulation results for both cases where the power of white noise are assumed to be identical for all five mobile stations. The system SNR is calculated from equation by replacing Pave(ε, R) with the average transmit power of the BS.

It is observed that when the WSA algorithm is employed the difference between using UBA or ABPA is negligible although the latter yields a better performance. Moreover, the performance of the system using both SA and ABPA is close (within 1.5dB) to the "WSA+ABPA" case whose performance is nearly optimal [10]. It is clear that the complexity for the proposed SA algorithm along with the ABPA algorithm is much lower than the WSA method making it more favorable for the wireless OFDM systems.

Table 1: User and channel configurations for the MU-OFDM system

	Case 1		Case 2	
User (k)	R_k	Average Power Gain	R_k	Average Power Gain
1	100	0dB	24	0dB
2	100	0dB	24	+2dB
3	100	0dB	128	-4dB
4	100	0dB	128	+6dB
5	100	0dB	208	-8dB

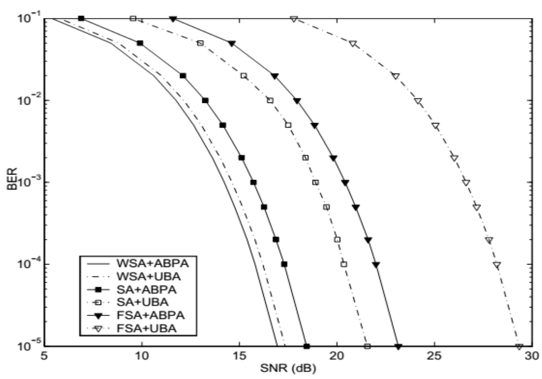

Fig. 5. Performance of the Subcarrier Allocation algorithm (case 1).

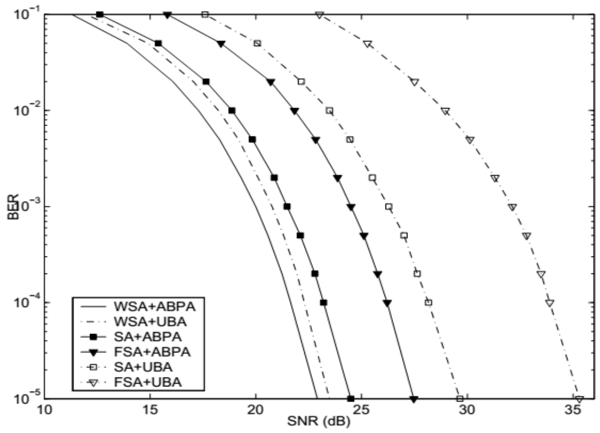

Fig. 6. Performance of the Subcarrier Allocation algorithm (case 2).

VIII. ON THE BIT AND POWER ALLOCATION FOR OFDM SYSTEMS WITH TIME-VARYING CHANNELS

Adaptive modulation has been recognized as an effective technique for improving the performance of wide-band communication systems over frequency-selective fading channels. we focus on the problem of resource allocation based on the noisy and outdated knowledge of the CSI. An earlier study in [11] shows that the state of a frequency-flat fading channel can be reliably predicted from the outdated observations across a long range of time. This motivates the prediction of frequency selective channels for the OFDM system since, using OFDM, the wide-band channel is transformed into a number of flat-fading sub-channels. We adopt the idea of CSI prediction and propose to perform resource allocation based on the predicted CSI.

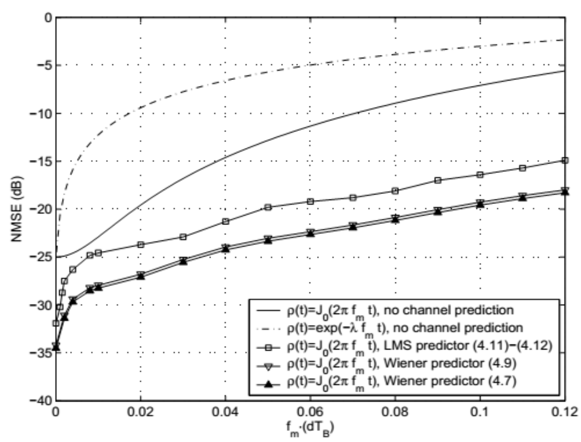

Fig. 7. Performance of channel prediction in terms of NMSE.

$$\mathrm{NMSE}_{\tilde{\mathbf{g}}(k)} = 2\left[1 - \mathrm{Re}(\rho(dT_B))\right] + E(\|\mathbf{e}\|^2)/E(\|\mathbf{g}\|^2) \tag{8}$$

The above equation shows that if the outdated channel estimate is used as a prediction of the current CSI, the associated NMSE is not only determined by the signal to noise ratio (SNR) of the channel estimation method, but also the autocorrelation function ρ(·). It turns out that in this case the effect of the channel autocorrelation function is more significant than that of the estimation error. The NMSEs calculated from above equation using these two correlation functions have been plotted with respect to fmdTB in Figure 7, where the SNR in the CIR estimation, namely the value of $E(\|\mathbf{e}\|^2)/E(\|\mathbf{g}\|^2)$, has been fixed to be 25dB. Fig. 7 illustrates that, when a delayed version of the estimated CIR is used for future CIR prediction, a small delay may result in large errors in CIR prediction even in cases where the estimation error is at an acceptable level (SNR=25dB).

IX. MAXIMUM LIKELIHOOD RECEIVER FOR THE MULTIBAND KEYING SIGNALS IN AWGN CHANNEL

Ultra Wideband (UWB) communication is now receiving a great deal of attention from the research community. The FCC has allocated a band of several giga hertz (3.1GHz – 10.6GHz) for the prospective UWB systems. According to FCC, a signal is qualified to be a UWB signal when it occupies a -10dB bandwidth which exceeds 500MHz or 20% of its center frequency [12].

The block diagram of the optimal receiver is illustrated in Figure 8. For each of the P branches, the MPSK receivers output not only the estimated signal phases but also the corresponding correlation values. Thus in the case of large signal to noise ratio (SNR), the symbol error probability can be approximated by [13] It can be shown that the Euclidean distance between any pair of MBK symbols which have different frequency sequences is no less than 2√Es for any P and M.

$$P_e \approx \begin{cases} P(2P-1)\, Q\left(\sqrt{\frac{2E_s}{N_0}}\right), & M = 2 \\ 2P\, Q\left[\sqrt{\frac{2E_s}{N_0}\sin^2\left(\frac{\pi}{M}\right)}\right], & M > 2 \end{cases} \tag{9}$$

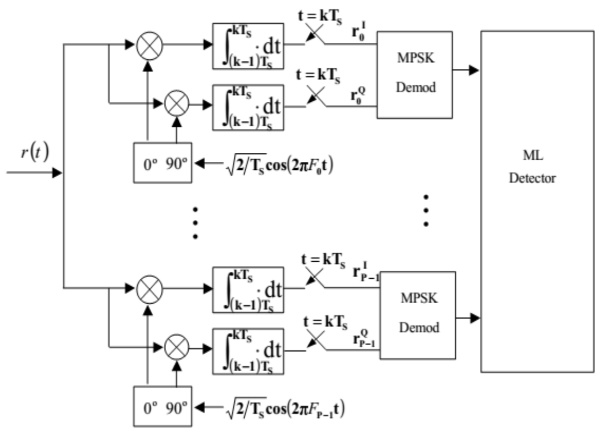

Fig. 8. Maximum Likelihood receiver block diagram.

The performance of the optimal receiver for QPSK (M=4) & 4 carrier frequencies (P = 4) and BPSK (M=2) & 5 carrier frequencies (P = 5) is simulated. For larger values of P the simulation of the ML decision rule becomes excessively time consuming as a result of exhaustive search. Figure 9 shows the symbol error rate (SER) of the optimal ML decision rule vs Eb/N0 for the two cases described above. In this figure we also plot the symbol error rate obtained from the approximations in above equation. In both cases the simulation results match the approximation quite well, especially for large Eb/N0. This result holds for other values of M and P as well.

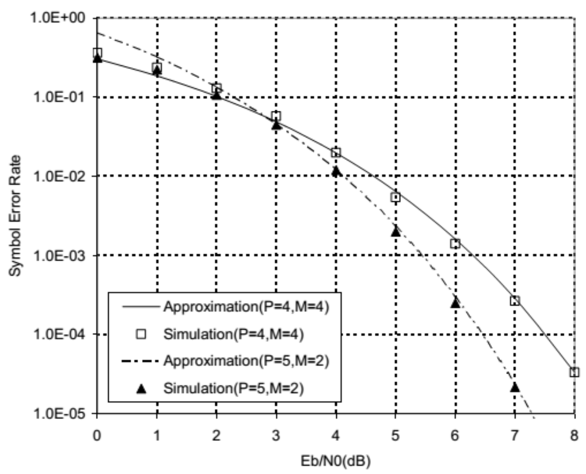

Fig. 9. Performance of optimal receiver

X. CONCLUSIONS

In this paper, optimal resource allocation for multiuser orthogonal frequency-division multiplexing systems has been investigated. Simulation results are provided for OFDM system over frequency selective fading channels.

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